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Evidence for an Extended SZ Effect in WMAP Data

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ABSTRACT

We have cross-correlated the WMAP data with several surveys of extragalactic sources and find evidence for temperature decrements associated with galaxy clusters and groups detected in the APM Galaxy Survey survey and the ACO catalogue. We interpret this as evidence for the thermal Sunyaev-Zeldovich (SZ) effect from the clusters. Most interestingly, the signal may extend to ≈1 deg ($\approx 5h^{-1}$ Mpc) around both groups and clusters and we suggest that this may be due to hot 'supercluster' gas. We have further cross-correlated the WMAP data with clusters identified in the 2MASS galaxy catalogue and also find evidence for temperature decrements there. From the APM group data we estimate the mean Compton parameter as $y(z < 0.2) = 7 \pm 3.8 \times 10^{-7}$. We have further estimated the gas mass associated with the galaxy group and cluster haloes. Assuming temperatures of 5 keV for ACO clusters and 1 keV for APM groups and clusters, we derive average gas masses of $M(r < 1.75h^{-1}\,\mathrm{Mpc}) \approx 3 \times 10^{13} h^{-2} M_{\odot}$ for both, the assumed gas temperature and SZ central decrement differences approximately cancelling. Using the space density of APM groups we then estimate ${\Omega_0}^{gas} \approx 0.03h^{-1}(1\,\mathrm{keV}/kT)(\theta_{max}/20')^{0.75}$. For an SZ extent of $\theta_{max} = 20'$, $kT = 1$ keV and $h = 0.7$, this value of ${\Omega_0}^{gas} \approx 0.04$ is consistent with the standard value of ${\Omega_0}^{baryon} = 0.044$ but if the indications we have found for a more extended SZ effect out to $\theta_{max} \approx 60'$ are confirmed, then higher values of ${\Omega_0}^{gas}$ will be implied. Finally, the contribution to the WMAP temperature power spectrum from the extended SZ effect around the $z < 0.2$ APM+ACO groups and clusters is 1-2 orders of magnitude lower than the $l = 220$ first acoustic peak. But if a similar SZ effect arises from more distant clusters then this contribution could increase by a factor > 10 and then could seriously affect the WMAP cosmological fits.

Key words: cosmic microwave background - galaxies: clusters

1 INTRODUCTION

The Wilkinson Microwave Anisotropy Probe (WMAP) cosmic microwave background (CMB) anisotropy experiment has published its first year data and has already provided remarkable results. It has confirmed that the first peak in the power-spectrum occurs at $l = 220 \pm 10$ and has provided an excellent further detection of the second peak (Hinshaw et al. 2003). In the first instance, these new results seem to provide further support for the standard ΛCDM cosmology (Spergel et al. 2003). But the main new result from WMAP is the detection of polarisation at large scales which can only have come from an epoch of reionisation at $10 < z < 20$ (Kogut et al. 2003). This results in a significant, (≈30 per cent), reduction of the acoustic peak heights due to Thomson scattering and shows that the CMB anisotropies are seriously affected by low red-shift galaxy formation physics. Furthermore, WMAP also finds a low quadrupole in the temperature power-spectrum (Hinshaw et al. 2003) and this is also unexpected if the Integrated Sachs-Wolfe (ISW) effect caused by relatively recent domination of the cosmological constant is present. Therefore, although WMAP data supports the standard model, there are significant problems and already strong evidence that the temperature spectrum is affected by cosmic foregrounds such as the re-ionised intergalactic medium at $10 < z < 20$.

Here we investigate the possibility that other low redshift processes have filtered the WMAP temperature spectrum. In particular, we shall search for Sunyaev-Zeldovich (SZ), inverse Compton-scattering of microwave background photons by hot gas in clusters. Various authors have made model dependent predictions for contamination of the CMB data from the SZ effect and usually concluded that the contaminating effects were small (Refregier et al. 2000a,b; Komatsu & Kitayama 1999). The new WMAP data gives a first real opportunity to make empirical checks of the level

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of contamination by direct cross-correlation of the high resolution 94GHz W band with galaxy cluster data. The WMAP team themselves have presented evidence for both SZ and radio source contamination in the WMAP data. Bennett et al. (2003) list 208 point sources detected at more than 5σ in the WMAP data and identified them as radio galaxies and quasars. They also find significant WMAP W band SZ detections of the brightest X-ray clusters such as Coma and also found a 2.5σ detection of the SZ effect in the XBACS sample of 242 X-ray bright Abell clusters (Ebeling et al. 1996). However, they only looked for SZ decrements on the scale of the WMAP beam and did not explore any larger scales.

While this paper was in preparation, several other related papers have appeared. Boughn & Crittenden (2003) and Nolta et al. (2003) have claimed evidence for the ISW effect in the WMAP data from cross-correlation with the NVSS catalogue. Diego, Silk & Sliwa (2003) have cross-correlated X-ray data and the WMAP data. Similarly Fosalba & Gaztañaga (2003) have cross-correlated APM galaxies and WMAP data; they find a marginal detection of the ISW effect at 5-10 deg scales and suggest that the lack of a detection at smaller scales may be due to cancellation with an SZ effect. Hernandez-Monteagudo & Rubino-Martin (2003) have obtained upper limits on diffuse SZ emission from superclusters from failing to find any cross-correlation with the Abell-Corwin-Olowin (ACO) and other cluster catalogues but they did find significant correlations from individual clusters. Giommi & Colafrancesco (2003) have claimed to detect significant blazar contamination in WMAP and Boomerang data. Afshordi, Loh & Strauss (2003) have claimed the detection of SZ, ISW and point sources in a power spectrum analysis of WMAP data and the 2MASS galaxy catalogue.

2 DATA

2.1 WMAP

The WMAP data has been published by Bennett et al. (2003) in HEALPix format. Here we shall principally use the WMAP W band data at 94 GHz because of its relatively high resolution compared to the other bands. The FWHM of the 94 GHz W beam is $12.'6$ compared to $19.'8$ at V (61 GHz), $29.'4$ at Q (41 GHz), $37.'2$ at Ka (33 GHz) and $49.'2$ at K (23 GHz). Although, none of the beams is exactly Gaussian (see Fig. 2 of Page et al. (2003)) we have found that Gaussians of the above FWHM are good approximate fits to cross-correlation results between faint radio point sources and WMAP data. We shall also use the Internal Linear Combination (ILC) map which has 1 deg resolution (Bennett et al. 2003). Also the W band has most sensitivity to the SZ effect via its high resolution, although perhaps has higher noise than the V band. The HEALPix WMAP data we shall use has equal area pixels of 49 arcmin^2. Where necessary, we shall use the Kp0 WMAP mask of Bennett et al. (2003) which mainly masks Galactic contamination but usually its effect is small because we shall generally be working at Galactic latitudes, $|b|$ >40 deg. The maps all use thermodynamic temperature and the cosmological dipole has already been subtracted from the data by the WMAP team.

2.2 Galaxy Cluster Catalogues

We shall be using three galaxy cluster catalogues. The first is the ACO catalogue of Abell, Corwin & Olowin (1989) which lists clusters with 30 or more members in a $1.5h^{-1}$ Mpc radius within 2 mag of the 3rd brightest cluster member. It assigns richness class ($0 \leqslant R \leqslant 5$) with Coma classed as $R = 3$. The Northern catalogue with $b > 40$ deg lists 2489 clusters with $R \geqslant 0$ the Southern catalogue with $b < 40$ deg lists 1346 such clusters. The sky density in the North is therefore 0.52 deg^{-2} and in the South it is 0.28 deg^{-2}. The sky density of $R \geqslant 2$ clusters is 0.063 deg^{-2} with an average redshift of $z = 0.15$.

We shall also use galaxy group and cluster catalogues derived from the APM Galaxy Survey of Maddox et al. (1990) which covers the whole area with $\delta < -2.5$ deg and $b < -40$ deg. These were identified using the same 'friends-of-friends' algorithm as Myers et al. (2003) and references therein. Circles around each APM galaxy with $B < 20.5$ are 'grown' until the overdensity, β, falls to $\beta = 8$ and those galaxies whose circles overlap are called groups. Minimum memberships, m, of $m \geqslant 7$ and $m \geqslant 15$ were used which define minimum group effective 'radii' of $1.'2$ and $1.'7$, since the APM galaxy surface density is $N \approx 750$ deg^{-2} at $B < 20.5$. We assume an average redshift of $z = 0.1$ for both APM samples. The sky density of groups and clusters is 3.5 deg^{-2} at $m \geqslant 7$ and 0.35 deg^{-2} at $m \geqslant 15$. Even at $m \geqslant 15$ there are differences between the ACO and APM catalogues; an $R = 0$ Abell cluster at $z = 0.15$ may contain only a galaxy sky density of 260 deg^{-2} within its $11.'5$ Abell radius compared to a minimum sky density of 5250 deg^{-2} for galaxies within the APM groups. Therefore the $R \leqslant 1$ ACO 'clusters' may accommodate much lower density galaxy associations than even the $m \geqslant 7$ APM groups which are guaranteed to sample higher density regions, albeit over smaller areas.

The third cluster catalogue is derived from the final data release of the 2MASS Extended Source Catalogue (XSC) (Jarrett et al. 2000) to a limit of $K_s \leqslant 13.7$. K-selected galaxy samples are dominated by early-type galaxies because of their red colours and early-type galaxies are the most common galaxy-type found in rich galaxy clusters. Therefore the 2MASS survey provides an excellent tracer of the high density parts of the Universe out to $z < 0.15$ and so provides a further test for the existence of the SZ effect. Using the above 2-D friends-of-friends algorithm, we have detected 500 groups and clusters with $m \geqslant 35$ members at the density contrast $\beta = 8$ in the $|b| \geqslant 10$ deg area. The 2MASS groups have average redshift, $z \approx 0.06$.

3 CROSS-CORRELATION TECHNIQUE

We search for correlated signals between the 5 (+ ILC) WMAP bands and the above datasets using a simple cross-correlation technique. The WMAP data are presented in the form of temperature differences with respect to the global mean and we form the correlation function by calculating the average ΔT in annuli around each cluster as a function of angular distance, θ, between the cluster and pixel centres.

At large θ, where the average background may be expected to be sampled, the average in particular areas of the sky may not return to zero, probably because of Galactic contamination. We therefore always calculate the simple average of all temperature differences in the sub-area of sky used and plot this on the cross-correlation result as the effective zero level (solid lines).

The errors are calculated by repeated Monte Carlo random realisations of the cluster centres across the WMAP area used. The realisations always have the same number of points as the parent sample and 100 realisations were done in each case. The effect of clustering of clusters is included in the realisations; the clustering amplitude is matched to that of the cluster sample under consideration. In the cross-correlation functions, there is significant correlation between the results at different angles, θ, so we have also calculated Monte-Carlo errors in the integrated bins used to quote overall significances. The Monte Carlo realisations also quite accurately return results that are close to the overall average, indicating that our cross-correlation technique is free of any systematics. We note that our error analysis will miss variance from CMB modes of order the cluster catalogue size. Since this size is generally $\gtrsim 50\,$deg, it is not expected that error estimates on angular scales $\theta \lesssim 1\,$deg will be seriously affected, although on larger scales our quoted errors may increasingly be underestimates.

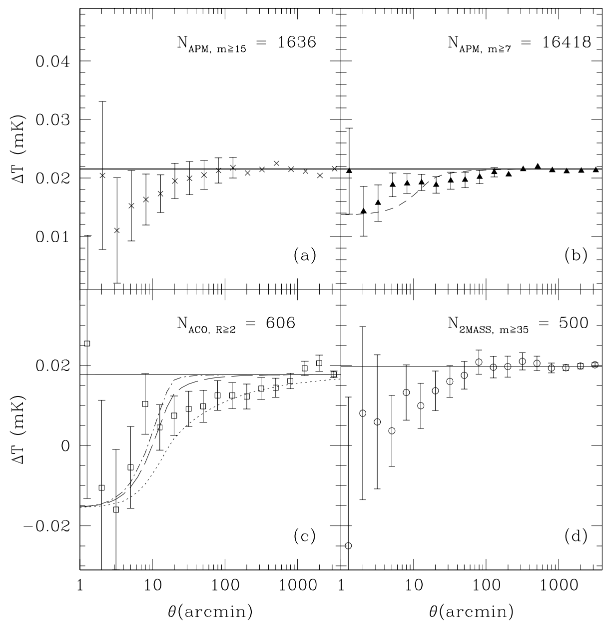

Figure 1. (a) Cross-correlation of WMAP 94 GHz W band data with $m \geqslant 15$ APM groups and clusters. (b) Cross-correlation of WMAP 94 GHz W band data with $m \geqslant 7$ APM groups and clusters. The dashed line is an isothermal SZ model with $\Delta T(0) = 0.015\,$mK, $\theta_c = 2.'3$, $\beta = 0.75$ convolved with a Gaussian beam profile with $\sigma = 5.'25$. (c) Cross-correlation of WMAP 94 GHz W band data with ACO $R \geqslant 2$ clusters for combined ACO $|b| > 40\,$deg N+S samples. The dashed, dotted and dot-dash lines are isothermal SZ models with $\theta_c = 1.'5$ and $\Delta T(0) = 0.083\,$mK, $\beta = 0.75$; $\Delta T(0) = 0.050\,$mK, $\beta = 0.5$; and $\Delta T(0) = 0.12\,$mK, $\beta = 1.0$, convolved as in (b). (d) Cross-correlation of WMAP 94 GHz W data with 500 galaxy groups and clusters selected by friends-of-friends algorithm ($\beta = 8$, $m \geqslant 35$) from the $K_s < 13.7$ 2MASS XSC. In all cases the solid lines represent the average ΔT obtained over the area used. Monte-Carlo errors including the effects of clustering of clusters are shown.

4 CROSS-CORRELATION RESULTS

In Fig. 1a,b we first present the results from cross-correlating our APM groups and cluster centres with the WMAP W band data. We consider the two APM cluster samples with $m \geqslant 15$ and $m \geqslant 7$ members. Both samples show indications of anti-correlation with respect to the 94 GHz data. Relative to the overall mean, the integrated significances for the $m \geqslant 15$ sample range from 1.7σ at $\theta < 10'$ to 1.0σ at $\theta < 30'$. The significances for the $m \geqslant 7$ sample range from 2.0σ at $\theta < 10'$ to 1.8σ at $\theta < 30'$. In the case of the $m \geqslant 15$ clusters, the size of the anti-correlation is $\Delta T \approx -0.01\,$mK on WMAP pixel scales. It is also interesting that the size of the signal only goes down slightly to $\Delta T \approx -0.008\,$mK at small scales for the $m \geqslant 7$ sample and here the anti-correlation appears to extend beyond the beam-size, only reducing to 1.5σ at $\theta \approx 60'$. The anti-correlation signal seen at small θ ($\leqslant 10'$) is consistent with what is expected at this frequency for the temperature decrement caused by the SZ effect (Refregier et al. 2000a). The surprise is that it can be seen out to $\approx$1 deg scales and that it persists in groups with a sky density of $3.5\,\mathrm{deg}^{-2}$, a factor $\approx$30$\times$ higher than that of the Abell clusters.

We now turn to the ACO catalogue to see if there is any confirmation of this tentative detection of extended anti-correlation around the APM groups and clusters. When the full ACO catalogue at $|b| > 40\,$deg including clusters of all richnesses, was used only an insignificant anti-correlation was found. The catalogue was then cut back to $R \geqslant 2$ and the result changed dramatically and consistently in both Hemispheres. Based on the remaining 229 clusters with $b > 40\,$deg and the remaining 377 clusters with $b < -40\,$deg, significant anti-correlation is again seen out to scales of $\theta \approx 1\,$deg or $\approx 7.5h^{-1}\,$Mpc (see Fig. 1c). The Monte-Carlo errors indicate that the effect is significant at the $\approx 2.1\sigma$ level for $\theta < 10'$ and at the $\approx 2.2\sigma$ level for $\theta < 1\,$deg in the N+S sample. Our interpretation is that the $R = 0, 1$ clusters may have too low densities to produce a strong SZ effect. We conclude that there is a significant anti-correlation out to $\approx 1\,$deg scales between the ACO $R \geqslant 2$ cluster catalogue and the WMAP W band data, confirming the tentative detection seen in the APM group and cluster catalogues, and that this is likely to be caused by the SZ effect.

Figs. 2 (a-f) shows that the ACO $R \geqslant 2$ clusters also produce anti-correlations in all the other frequency bands, including the ILC. In terms of the predicted SZ frequency dependence according to equations (11) and (13) of Refregier et al. (2000a) this is expected because relative to the W band the V, Q, Ka and K bands the SZ decrement should increase by the factors 1.16, 1.21, 1.25 and 1.25. The poorer resolution of the low frequency WMAP bands makes the detection of the decrements more unexpected but it is explained by the apparent persistence of the signal out to scales well in extent of the W band beam. The frequency dependence of the SZ signal appears statistically consistent with the SZ prediction (dashed lines) in all except the K band where the combination of poor resolution and residual Galactic contamination may be the cause of the poor fit. However, the errors are too large to discriminate between the SZ and CMB spectral indices. It is this spectral simi-

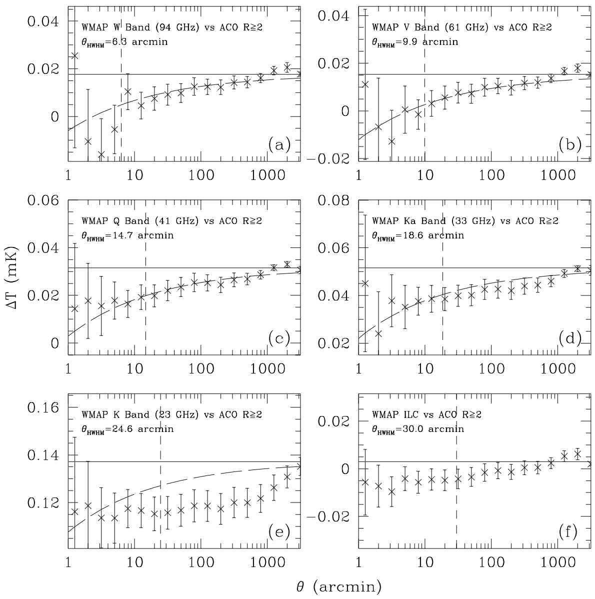

Figure 2. Cross-correlation of WMAP data in the W, V, Q, Ka, K and ILC bands with 606 $|b| > 40$ deg ACO clusters. The SZ decrement can be seen in each band. In all cases the solid line is the simple average ΔT over the area surveyed, and the vertical short-dashed line indicates the beam half-maximum in each band. The long-dashed line shows a $\theta^{-1/3}$ fit to the W band, scaled for the SZ frequency dependence to the other bands, which can be used as a reference line for the frequency dependence.

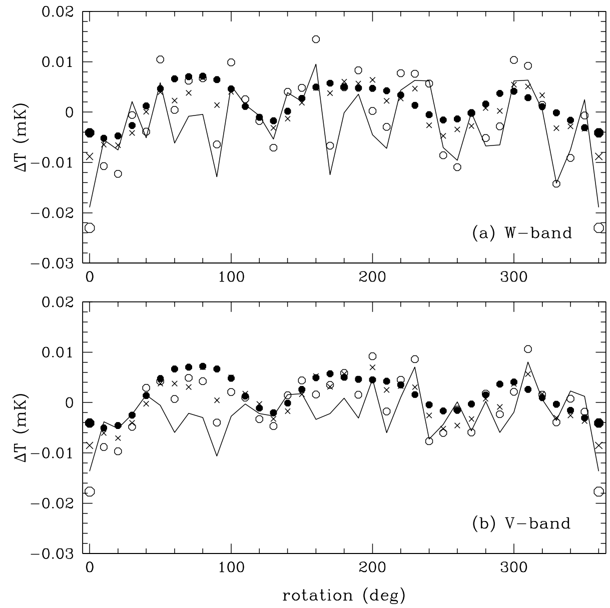

Figure 3. (a) Cross-correlation of WMAP W band with the 606 ACO clusters after rotation about the Galactic Poles by adding Δl to the cluster's Galactic longitude. The open circles represent the average ΔT with $\theta < 6.'3$ (the beam half-maximum in W), the crosses represent the average ΔT with $\theta < 60'$ and the filled circles represent the average ΔT with $\theta < 500'$. In each case, the average ΔT over the area surveyed has been subtracted. The $\theta < 6.'3$ and $\theta < 60'$ results at zero rotation lie significantly below the others but the equivalent $\theta < 500'$ result does not. The solid line represents the difference between the $\theta < 6.'3$ and the $\theta < 500'$ results which shows the effect on the beam-size result if the anti-correlation observed at $\theta < 500'$ is assumed due entirely to systematics. (b) As (a) for the V band. Here the open circles and solid line correspond to $\theta < 9.'9$, the beam half-maximum in V.

larity which makes it difficult to reject SZ contamination in the CMB maps and which explains our SZ detection in the 'clean' ILC map. The APM clusters and groups also show anti-correlations in the V and Q bands but less so in the other bands, probably because of the lower resolution.

To check if the cross-correlation results contain artefacts characteristic of residual Galactic foreground contamination, we have cross-correlated the ACO clusters with the WMAP foreground maps of Bennett et al. (2003) and find no indication of any strong systematics. We also note that we have obtained results for the SZ decrements from the ACO, APM and 2MASS clusters from the 'foreground-cleaned' map of Tegmark, de Oliveira-Costa & Hamilton (2003) that are entirely consistent with those found from the ILC map; the detection of the same anti-correlation in both of these 'clean' maps further argues against the possibility that the anti-correlation is due to foreground systematics.

As a further powerful check against systematics caused by foreground contamination, we have also applied the cross-correlation analysis after rotating the ACO $R \geqslant 2$ clusters around the Galactic Poles with respect to the WMAP W and V band data. Fig. 3 shows the W and V band cross-correlation signals (relative to the mean ΔT) integrated to the beam half-maximum ($\theta < 6.'3$ for W, $\theta < 9.'9$ for V), $\theta < 60'$ and $\theta < 500'$ measured at intervals of $\Delta l = 10$ deg of Galactic longitude. The solid line shows the difference between the beam half-maximum and the $\theta < 500'$ angular scales; this is to test for the persistence of the beam-size anti-correlation under the assumption that the $\theta < 500'$ result is entirely due to systematic effects. The anti-correlation at the beam half-maximum is clearly significant whether measured relative to the overall mean (3.1σ for W, 3.6σ for V) or the $\theta < 500'$ results (2.8σ for W, 3.1σ for V). The anti-correlation at $\theta < 60'$ also remains significant whether measured relative to the overall mean (2.3σ for W, 2.2σ for V) or relative to the $\theta < 500'$ results (2.0σ for W, 1.7σ for V). Although the rotated results appear more correlated at $\theta < 60'$ than at $\theta < 6.'3$, implying these latter significances be treated with caution, it remains the case that for the $\theta < 60'$ the zero rotation result shows the lowest ΔT. This is not the case for the $\theta < 500'$ points where several of the rotated points show both lower and higher excursions around zero than the zero rotation result. Clearly there may be systematics which are beginning to dominate any real SZ signal at these very large scales. We conclude that the rotation experiments suggest that the observed temperature decrements around ACO clusters are significant from the beam-size out to $\theta < 60'$ and these results are robust to the assumption that the cross-correlation is dominated by possible systematics on $\theta < 500'$ scales.

Fig. 1(d) shows the cross-correlation of the 500 2MASS groups and clusters limited at $K_s < 13.7$ with the WMAP W band. Again the 2MASS data shows similar trends to the APM and ACO clusters with anti-correlation seen on scales of the beam and extending at marginal significance out to scales of ≈ 1 deg. Again the frequency dependence is consistent with an SZ signal (not shown). At the average 2MASS group redshift, $z \approx 0.06$, $\theta < 1$ deg corresponds to $r < 3h^{-1}$Mpc and thus here there is further evidence for possible extension of the SZ decrements to scales of order $> 1h^{-1}$Mpc.

5 DISCUSSION

We have found evidence for WMAP temperature decrements extending out to scales of $\theta \approx 1$ deg from galaxy groups and clusters, with hints that the decrements may extend to even larger scales. Previous cross-correlation of the ACO catalogue with the Rosat All-Sky Survey has shown diffuse X-ray emission from ≈ 1 keV gas extending out to ≈ 2 deg from $D = 5$, $R \geqslant 1$ Abell Clusters, comparable to the scale of the anti-correlation seen in Fig. 1c (Soltan, Freyberg & Hasinger 2002). Thus, based on this indication that the anti-correlation may be caused by the SZ effect originating from diffuse 'supercluster' gas, we make a first order calculation of the overall Compton parameter, y. From Refregier et al. (2000a) we use the relation $\Delta T_{SZ}/T_0 = yj(x)$ where T_0 is the CMB temperature, $x = h\nu/kT_0$ and $j(x)$ is a spectral function which takes the value $j(x) = -1.56$ at 94 GHz. The simplest route is to go via the $m \geqslant 7$ APM groups and clusters because these have the biggest space density and so are the most representative of average sightlines. These have a sky density of $3.5\,\mathrm{deg}^{-2}$ with an average SZ decrement that extends to $\theta > 0.5$ deg and so have a sky covering factor of approximately unity. For $0.1 < \theta < 0.5$ deg in Fig. 1b, ΔT is reasonably flat so that effects due to the WMAP beam may be small and in this range $\Delta T_{SZ} = -3.0 \pm 1.6\,\mu$K. Using the above relation with $T_0 = 2.726$ K, this converts into a value for $y(z < 0.2) = 7 \pm 3.8 \times 10^{-7}$. Now Refregier et al. (2000a) refer to Scaramella, Cen & Ostriker (1993) and Persi et al. (1995) as suggesting that 40 per cent of y originates at $z < 0.2$ in CDM models. On this assumption, we find $y(z < \infty) = 1.8 \pm 1.0 \times 10^{-6}$. This compares to the 3σ upper limit on the total integrated y parameter from the COBE-FIRAS measurement of the spectral distortion of the CMB of $y(z < \infty) = 2.2 \times 10^{-5}$ (Fixsen et al. 1996). The 3σ upper limit from cross-correlating COBE DMR and FIRAS is $y(z < \infty) = 4.5 \times 10^{-6}$ (Fixsen et al. 1997). Banday et al. (1996) found a 3σ upper limit of $\delta y(z < 0.2) < 1.5 \times 10^{-6}$ by cross-correlating COBE DMR with the ACO cluster catalogue. Thus our result is not inconsistent with these previous observational upper limits. We also note that our estimate of y is 2-3× higher than that predicted in the SCDM model of Scaramella, Cen & Ostriker (1993) and that it is similar to the value predicted in the ΛCDM model of Persi et al. (1995).

We next fit isothermal models to the SZ decrements for the ACO R⩾2 clusters. The models are taken from Equns. 15, 16 of Refregier et al. (2000a) and convolved with Gaussians to represent the beams. We assume the value of $\beta = 0.75$ quoted for Coma and a value of $\theta_c = 1.'5$ which is the Coma value scaled approximately to the $z = 0.15$ average redshift of the ACO sample. We find that 0.083 mK is the best fit for $\Delta T(0)$ compared to the 0.5 mK quoted for Coma. The results are shown in Figs. 1(b),(c). It can be seen that the data appears to show a more extended decrement than the model. The same model with $\beta = 0.5$ gives an improved fit at larger scales for $\Delta T(0)$ of 0.05 mK.

The cluster correlation function (Bahcall & Soneira 1983) suggests the number of excess clusters at $20' < \theta < 100'$ from an average cluster is ≈ 1.3. Based on the average decrement seen at $\theta < 20'$, we estimate this cluster excess will contribute $\Delta T = 0.5\,\mu$K, at $20' < \theta < 100'$, compared to the observed $\Delta T = 6\,\mu$K. Thus it does not seem possible for clustering of 'beam-sized' clusters to explain the extent of the decrement; an extended ($\theta \gtrsim 1$ deg) gas halo around individual clusters appears to be needed.

We next calculate the gas mass associated with an ACO $R \geqslant 2$ cluster. Using equation (16) of Refregier et al. (2000a) and assuming $kT = 5$ keV, $r_c = 0.2h^{-1}$ Mpc, the W band fit with $\Delta T(0) = 0.083$ mK gives a value for the central electron density, $n_0 = 1.8h \times 10^{-3}\,\mathrm{cm}^{-3}$. Integrating equn. (14) of Refregier et al. (2000a) with $\beta = 0.75$ to $r < 1.75h^{-1}$ Mpc ($\approx 13'$) then gives a gas mass of $M \approx 3 \times 10^{13} h^{-2} M_\odot$, which is not unreasonable compared to the X-ray gas mass of $M \approx 1 \times 10^{14} h^{-2.5} M_\odot$ detected within a similar radius in the Coma cluster (Lea et al. 1973).

A model with $\beta = 0.75$, $\theta_c = 2.'3$ and $\Delta T(0) = 0.015$ mK is shown to give a reasonable fit at small scales to the APM $m \geqslant 7$ sample in Fig. 1c. $\theta_c = 2.'3$ is the Coma value of $r_c = 0.2h^{-1}$ Mpc scaled to $z = 0.1$. Again there is evidence that the profile is more extended than the model.

We now proceed to calculate the average gas mass associated with an APM $m \geqslant 7$ group/cluster. Using equation (16) of Refregier et al. (2000a) and assuming $r_c = 0.2h^{-1}$ Mpc, the W band fit with $\Delta T(0) = 0.015$ mK gives a value for the central electron density, $n_0 = 1.6h \times 10^{-3}\,\mathrm{cm}^{-3}(kT/1\,\mathrm{keV})$. Integrating equn. (14) of Refregier et al. (2000a) with $\beta = 0.75$ to $r < 1.75h^{-1}$ Mpc ($\approx 20'$) then gives a gas mass of $M \approx 3 \times 10^{13} h^{-2} (kT/1\,\mathrm{keV}) M_\odot$. Since the APM groups and clusters are more numerous than the ACO clusters, we choose to use them to make an estimate of ${\Omega_0}^{gas}$. Assuming the space density of APM groups quoted by Croom & Shanks (1999); Myers et al. (2003) of $3 \times 10^{-4} h^3\,\mathrm{Mpc}^{-3}$ we find a value of ${\Omega_0}^{gas} \approx 0.03h^{-1}(1\,\mathrm{keV}/kT)(\theta_{max}/20')^{0.75}$. Assuming $h = 0.7$, $kT = 1$ keV and $\theta_{max} = 20'$ gives ${\Omega_0}^{gas} \approx 0.04$, close to the WMAP ${\Omega_0}^{baryon} = 0.044 \pm 0.004$ result (Spergel et al. 2003). There may be evidence in Fig. 1(b) for the SZ decrements to extend to $\theta_{max} \approx 60'$. In this case, the masses associated with APM groups rise by a further factor of ≈ 2 implying ${\Omega_0}^{gas} \approx 0.1$, now a factor of $\approx 2\times$ higher than the standard value for ${\Omega_0}^{baryon}$.

Is there any possibility that SZ decrements in the WMAP 94 GHz data could contaminate the acoustic peaks measurement? The question is interesting because the SZ correlations appear to extend out to $\theta \approx 1$ deg, the location of the first acoustic peak in the power spectrum. We have therefore run some simple models where circular areas representing clusters with SZ decrements are distributed at random over simulated CMB fields, laid down from Gaussian random fields drawn from CMBFAST power spectra (Zaldarriaga & Seljak 2000). If the SZ clusters have the same $3.5\,\mathrm{deg}^{-2}$ sky density as the APM $m \geqslant 7$ groups and we assume that they extend only to $\theta < 0.5$ deg with a decrement $\Delta T_{SZ} = -3\,\mu$K then the SZ power spectrum of clusters is two orders of magnitude below the first peak at wavenumber $l = 220$. However, if we assume that these groups and clusters extend unevolved in their gas content past the $z < 0.2$ APM limit out to $z < 0.5$, then the group + cluster sky density will rise to $\approx 50\,\mathrm{deg}^{-2}$. If we further assume values for the SZ extent and decrement which are at the high end of the ranges so far suggested, i.e. $\theta < 1\,\mathrm{deg}$ and $\Delta T_{SZ} = 5\,\mu\mathrm{K}$, then an SZ peak appears in the power spectrum which is of order ≈30 per cent of the amplitude of the first acoustic peak at $l = 220$. The consequences for the lower amplitude acoustic peaks at higher multipoles could be even more serious; we note that the temperature power spectrum from the CBI experiment already shows an excess at $l > 2000$ which may be due to a strong SZ effect from individual clusters (Pearson et al. 2002; Silk 2002). The above models might run up against the $y(z < \infty) = 4.5 \times 10^{-6}$ upper limit of Fixsen et al. (1997). *However, it is clear that the question of how much SZ effects contaminate the primordial power spectrum is re-opened by the spatial extent of the SZ signal found in our results.* Higher resolution CMB data and deeper group and cluster catalogues are needed to constrain further the SZ contribution from $z > 0.2$ clusters.

6 CONCLUSIONS

We have found evidence for anti-correlation between WMAP data and the positions on the sky of galaxy clusters derived from the ACO, APM and 2MASS surveys. We interpret the signal as caused by the SZ effect, inverse Compton scattering of the CMB photons by hot gas in groups and clusters of galaxies. The signal may extend to $\approx 1\,\mathrm{deg}$ scales around ACO clusters, implying they have extended gaseous haloes which may also constitute a diffuse gas component in superclusters. We estimate the mean Compton y parameter associated with $z < 0.2$ APM groups and clusters as $y(z < 0.2) = 7 \pm 3.8 \times 10^{-7}$. This is not inconsistent with previous upper limits and with expectations from CDM models. We have also estimated the average $R \geqslant 2$ ACO cluster gas mass assuming $kT = 5\,\mathrm{keV}$ and found this to be in reasonable agreement with X-ray observations of individual ACO clusters within the central radius, $r < 1.75h^{-1}\,\mathrm{Mpc}$. The average mass of APM groups+clusters is found to be $M(r < 1.75h^{-1}\,\mathrm{Mpc}) \approx 3 \times 10^{13} h^{-2} (1\,\mathrm{keV}/kT) M_{\odot}$ which gives ${\Omega_0}^{gas} \approx 0.03h^{-1}(1\,\mathrm{keV}/kT)$. For $kT = 1\,\mathrm{keV}$ and $h = 0.7$ this value for ${\Omega_0}^{gas} \approx 0.04$ is close to the value of ${\Omega_0}^{baryon} = 0.044$ in the standard model (Spergel et al. 2003). But because the X-ray temperatures are likely to be lower than $1\,\mathrm{keV}$ and because the SZ decrements show evidence for gas haloes which extend beyond $r = 1.75h^{-1}\,\mathrm{Mpc}$ then this value for ${\Omega_0}^{gas}$ could well prove to be a lower limit on the true value.

We have briefly investigated how SZ contamination might affect the location and shape of the acoustic peaks in the WMAP temperature and find that although there is little effect from the temperature decrements found so far, if they persist out to $z \approx 0.5$ with the amplitude and extent seen at $z < 0.2$, then even the first acoustic peak at the $1\,\mathrm{deg}$ scale could be significantly affected. Further cross-correlation analysis of deeper catalogues of groups and clusters will be needed to judge the seriousness of this potential SZ ‘contamination’.

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